Effects of Vertical Load and Velocity on the Isolation Bearing Performance. Lead-Rubber Bearings.

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ABSTRACT
In this paper results are reported obtained from an experimental investigation on the effects of axial load and strain rate on the performance of a full scale lead-core elastomeric bearing for bridge applications. Results are in line with similar tests performed on similar full scale bearings at the Caltrans SRMD Testing Facility, University of California San Diego. The response was analyzed with particular attention to the variation of critical performance characteristics in order to produce a set of information that will be implemented in a physically motivated numerical model (in progress).

INTRODUCTION
Even though the fundamental performance of the most common isolation devices is largely documented in literature, the behavior of large-size devices has been often extrapolated from experimental results of model scale prototypes and from numerical simulations. The main assumptions are usually related to the response at full displacement and under cycling at high speed (strain rate).
In this work, part of a larger experimental and analytical project sponsored by the California Department of Transportation (Caltrans), a series of tests were completed on a large full scale lead-core elastomeric bearing, suitable for bridge applications. The main goal of this experimental phase was to integrate the extensive database of performance data of bridge elastomeric devices tested as part of the Caltrans Toll Bridge Program. Particular attention was dedicated to the modifications of the bearing response due to the applied vertical loads and the testing velocity (strain rate).

DEVICE AND TESTING CHARACTERISTICS
The selected bearing represents a typical lead-rubber isolator for bridge applications. The rubber diameter is approximately 1050 mm with a cover of 19 mm and a lead-core diameter of 279 mm. The overall isolator height is about 490 mm including top and bottom steel plates that are 44 mm high. The bearing was tested at the Caltrans Seismic Response Modification Device (SRMD) Testing Facility at the University of California, San Diego campus. Details of the experimental program are reported in Table 1.
In order to obtain results for the three required cycles not corrupted by the effects of the table acceleration at the beginning and end of the tests, an entrance and exit half loop was introduced. The amplitude of this starting and ending ramps was equal to the maximum test amplitude and

the required peak velocity was achieved at the point of zero horizontal displacement. Three cycles were completed for each test except for the 6 full cycles of tests cb19 and cb20 (see Table 1). A sinusoidal waveform input was utilized for all the tests.

Table 1. Testing Summary

Test name	cb1	cb2	cb3	cb4	cb5	cb6	cb7	cb8
Vert. load (kN)	2224	4004	5783	2224	4004	5783	2224	4004
Peak vel. (mm/s)	0.76	0.76	0.76	355	355	355	711	711
Freq. (Hz)	0	0	0	0.186	0.186	0.186	0.371	0.371

Test name	cb10	cb11	cb12	cb13	cb14	cb15	cb16	cb17
Vert. load (kN)	1335	2224	3114	4004	4893	5783	2224	4004
Peak vel. (mm/s)	957	957	957	957	957	957	1270	1270
Freq. (Hz)	0.5	0.5	0.5	0.5	0.5	0.5	0.66	0.66

Test name	cb19	cb20	cb19: 3 cycles at 76.2 mm, 3 cycles at 304.8 mm
Vert. load (kN)	3114	3114	
Peak vel. (mm/s)	957	957	cb20: 2 cycles at 76.2 mm, 2 cycles at 152.4 mm,
Freq. (Hz)	0.5	0.5	2 cycles at 304.8 mm

The selection of the vertical load range and of the test frequency was motivated by the focus of this project on the effects of the vertical load and the test peak velocity. For this reason, the peak displacement applied was maintained constant for all the tests at a value of 304.8 mm, equivalent to 100% shear strain. The vertical load ranges between 2224 kN and 5783 kN for all the test velocity sets. The design vertical load for this specific bearing and for its specific bridge application was 2480 kN. A lower limit for the vertical load (1335 kN) was also included in test cb10.

Tests cb1, cb2 and cb3 represent the low velocity tests and were used as a reference to study the effects of the higher strain rates. Test cb19 and cb20 were designed to investigate the response variation of the device for a gradual increase of the displacement amplitude.

Tests were conducted with an interval of 30 min between subsequent runs in order to re-condition the bearing to a common level of initial temperature.

TEST RESULTS
Peak Shear Force

Despite the scatter of results, at a given vertical load, due to the effect of the test velocity, a quite constant response over the vertical load range was recorded. The results associated to the very slow tests (cb1, cb2, cb3) are in a range of peak shear force of 706.8 kN to 766.3 kN with a maximum reduction between the first and the third cycle equal to 5%. The effect of the vertical load appears to contribute, for these tests, only for a maximum of 36 kN in the first cycle. For tests at higher velocities, the different vertical loads generate a maximum variation of the peak force values equal to 4% for the first cycle at the velocity of 711 mm/s. The test velocity appears more effective on the shear force results than the amplitude of the applied vertical load. The first cycles appear to be the most sensitive to the strain rate effect with a maximum variation of 70.6%, 73.8% and 64.5% for vertical loads equal to 2224 kN, 4004 kN and 5783 kN,

respectively. For the second and third cycle the previous variations reduce to a consistent average of 45% and 30%, respectively. The performance appears very symmetric between positive and negative forces, except for the first cycle, where the positive results exceed the forces in the reversed direction of motion.

Yield Shear Force Q_d

The yield shear force is calculated according to equation (1), where $Q_1{}'$, $Q_1{}''$, $Q_2{}'$, and $Q_2{}''$ are the shear forces at 50% of the peak horizontal displacements (d_{max} and d_{min}):

$$Q_d = \left[\frac{Q_1{}'' d_{max}/2 - Q_1{}' d_{min}/2}{(d_{max} - d_{min})/2} - \frac{Q_2{}' d_{max}/2 - Q_2{}'' d_{min}/2}{(d_{max} - d_{min})/2} \right] / 2 \tag{1}$$

By definition and due to the sinusoidal shape of the input motion, Q_d corresponds to the average shear force experienced by the bearing at peak velocity during each cycle.

The trend of the effect of the vertical load amplitude on the average yield shear forces appears very similar to what observed in terms of maximum force. The maximum change in the shear force, at a given speed, is equal to 7.6% (occurring at 711 mm/s). Lower variations due to the different vertical loads are experienced at the other test velocities. The force values corresponding to the tests at 0.76 mm/s indicate a negligible variation with loads and cycles. The larger scatter between Q_d values is associated with the result of the first cycle. At constant vertical load, the effect of the strain rate was noticed to be more significant than what observed in terms of peak shear force. For the first cycle the increasing test velocity is associated to a Q_d increase of 95%, 103% and 89% at the three vertical load increasing levels, respectively. The variation is reduced to an average increment of 67% and 46% for the second and the third loop, respectively.

In order to establish a parameter for a numerical model, in terms of variation of yield shear force between cycles, the results were normalized to the data obtained from the second loop. The approach to refer to the second loop, as a reference cycle, allows comparing the results to a sort of "average" performance of the device, isolated from peculiar conditions introduced at the beginning and the end of the test. Figure 1 reports the Q_d results after normalization to the yield shear force of the second cycle (Q_{d2}) for different vertical loads (a) and velocities (b). For bearing performance under high strain rate, an average reduction of 25% and 15% appears to be reasonable for the transition from the first to the second cycle and from the second to the third cycle, respectively.
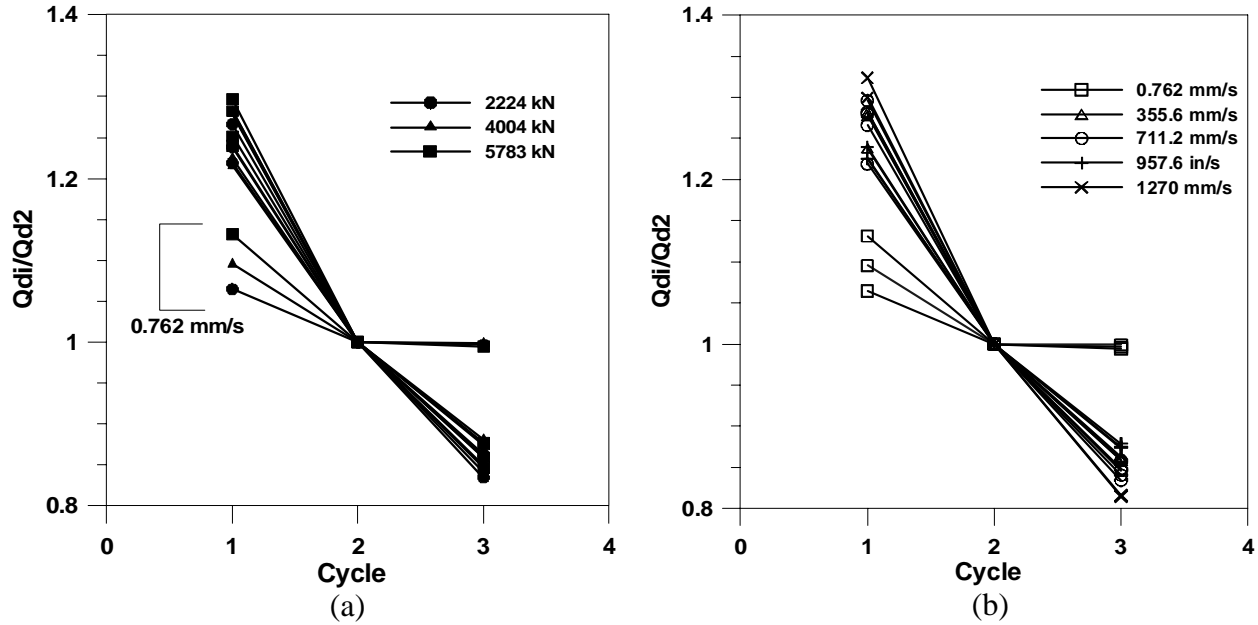
Figure 1. Ratio of Yield Shear Force of Each Cycle to the Force of the Second Cycle

Effective (K_{eff}) and Post-Yield Stiffness (K_d)

The effective stiffness was calculated, for each cycle of loading, as indicated in the AASHTO Guide Specifications (AASHTO, 2000).

Figure 2 shows the values of K_{eff} for the set of completed tests plotted versus the peak test velocity. With the exception of the absolute peak of 3.7 kN/mm, associated with test cb7b, the solid lines indicate a negligible difference between responses under different vertical loads.
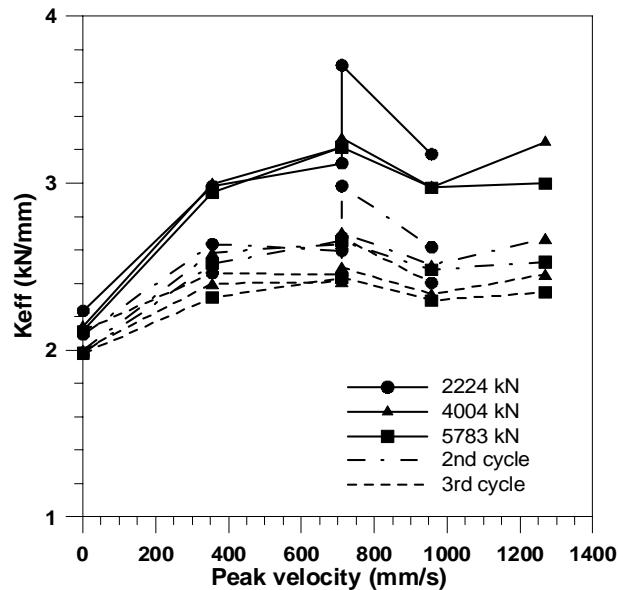

Figure 2. Effective Stiffness vs Testing Speed and Vertical Loads

Comparison between slow and fast motions indicates instead a general increase of the effective stiffness with the test speed particularly evident for the first cycle. The peak increment of the

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effective stiffness due to the test velocity confirms the constant trend across the range of vertical loads and was calculated as 52%, 34% and 22% for the first, second and third cycle, respectively. The normalization of the effective stiffness to the value of the second cycle indicates a wider scatter of results for the first cycle, for both load and velocity variation. The spread of results appears limited for the third cycle. The average value of normalized effective stiffness for the first and third cycle is 1.2 and 0.95, respectively, for tests at high speed. The reduction of K_{eff} for slow speed tests appears to occur only between the first and the second cycle, with a decrease of about 5%.

The post-yield stiffness K_d was calculated by equation (2):

$$K_d = \left[\frac{Q_1' - Q_1''}{(d_{max} - d_{min})/2} + \frac{Q_2'' - Q_2'}{(d_{max} - d_{min})/2} \right] / 2 \qquad (2)$$

The post-yield stiffness results (K_d) are plotted in Figure 3 and indicate a slightly higher effect of the applied vertical load compared to what obtained in terms of effective stiffness. A uniform reduction is visible with cycling loading and a consistent peak value is achieved at a maximum test velocity of 957 mm/s. For all the cycles and the test velocity values, the increase of the vertical load is associated with a reduction of post-yield stiffness.
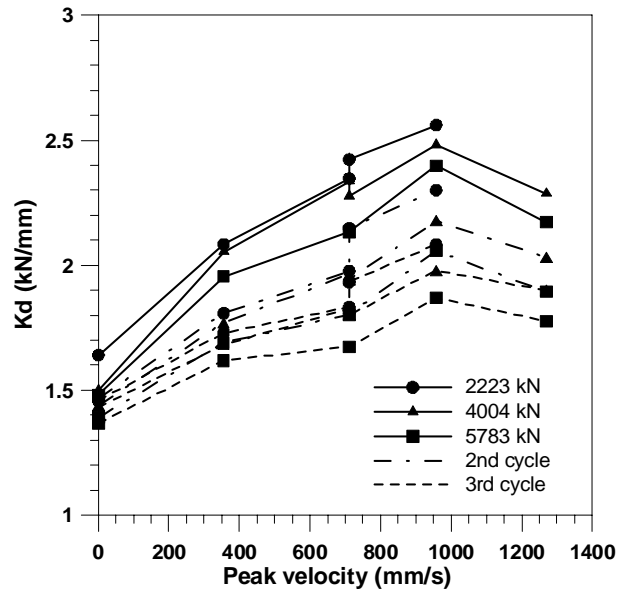

Figure 3. Post-Yield Stiffness vs Testing Speed and Vertical Loads

Table 2 reports the maximum variation, in percentage, at different velocity levels.
The effect of the test velocity is quite significant for the first cycle, with an average increase of 60% with strain rate, with respect to the slow tests. It is visible a peak stiffness value consistently achieved at 957 mm/s. For successive loops, the increase of K_d at high test speed follows a trend consistent with what observed for the first cycle of motion and reaches an average of about 50% and 40% for the second and third cycle, respectively. For the high speed tests an average ratio to the K_d value of the second cycle is 1.15 and 0.93, for the results of the first and third cycle, respectively.

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Table 2. Maximum reduction (%) of K_d due to increasing vertical load, for different test velocities and cycles

Cycle	v = 0.76 mm/s	v = 355 mm/s	v = 711 mm/s	v = 957 mm/s	v = 1270 mm/s
1	-9.7	-6.2	-12.0	-6.6	-4.8
2	-4.8	-6.1	-15.8	-10.8	-6.9
3	-6.8	-6.5	-13.4	-10.5	-6.8

Damping

Figure 4 reports the comparison in terms of damping ratio, for tests at constant shear strain and low and high testing velocity.

The damping ratios were calculated according to equation (3), where *EDC* represents the hysteresis loop area and Δ is the peak displacement:

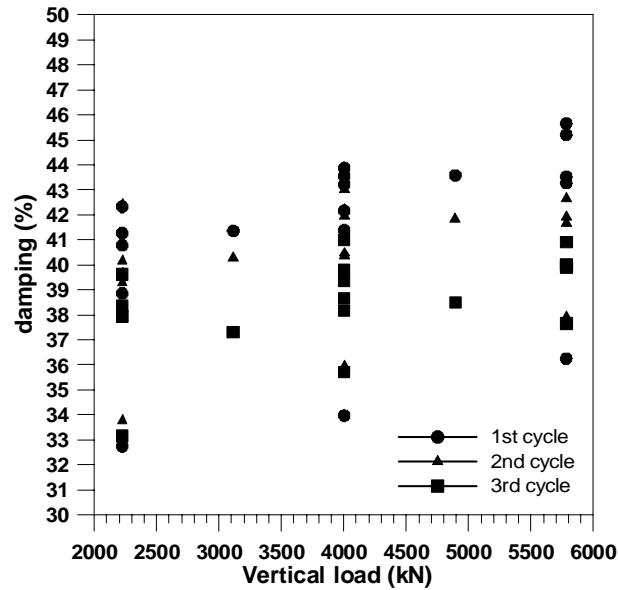$$\beta = \frac{1}{2\pi} \frac{EDC}{K_{eff}\Delta^2} \tag{3}$$

Figure 4. Damping ratio vs Vertical load

The effects of the vertical load on the damping ratio results appear limited, with maximum variation equal to 5-10% for the first cycle, 5-12% for the second cycle and 5-13% for the third cycle. The highest effect was noticed for the tests at very slow velocity.

More visible effects are observed due to the variation of the peak velocity. For the first cycle a constant increase of damping ratio, equal to 29%, is associated with the high velocity tests, with respect to the slow tests. This increase is experienced for all the values of vertical load. The increment reduces to an average of about 19% and 14% for the second and third cycle, respectively. For the second and third cycle, the increase in damping ratio due to velocity effects decreases with increasing vertical loads.

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The normalized plots of Figure 5 clearly show the scatter of results, particularly in terms of variation of the damping ratio from the first cycle to the second cycle.
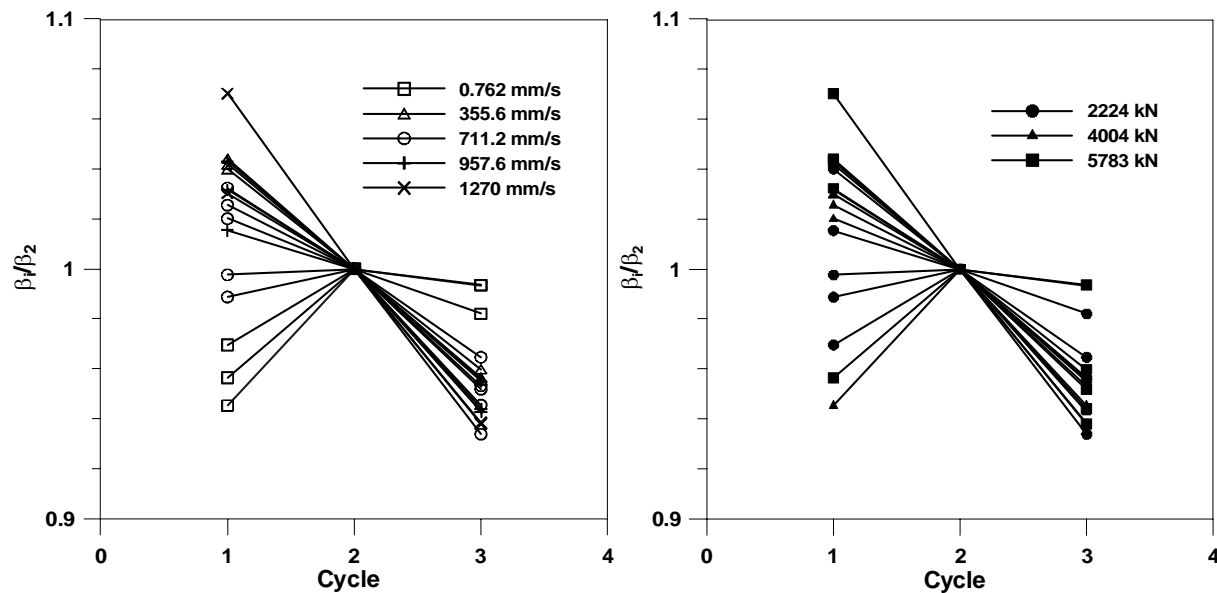

Figure 5. Normalized Damping Ratio

Gradual Increase of Displacement Amplitude

Tests cb19 and cb20 were completed in order to evaluate the effect of preliminary low amplitude cycles on the peak response parameters of the full amplitude loops. The result of the these two tests were compared with the results of test cb12 that was completed at the same amplitude, vertical load and speed. Data indicate a uneven effect of the preliminary low amplitude cycles. A maximum increment of peak force was found in the order of 18.6% and 28% for tests cb19 and cb20, respectively.

CONCLUSIONS

A full scale bridge lead-rubber bearing was tested under a wide range of applied vertical loads and test velocities. The results indicate a moderate effect of the vertical load values, but a significant effect of the strain rate on all the significant response parameters. The design of a numerical model, able to take into account these effects is in progress.

REFERENCES

AASHTO (2000), "Guide Sp[ecifications for Seismic Isolation Design", American Association of State and Highway and Transportation Officials, Washington, D.C.

Aiken, I.D., Kelly, J.M., Clark, P.W., Tamura, K., Kikuchi, M., Itoh, T., (1992) "Experimental Studies Of The Mechanical Characteristics Of Three Types Of Seismic Isolation Bearings", 10th World Conference on Earthquake Engineering, Madrid, Spain, July

Thomson, A.C., Whittaker, A.S., Fenves, G.L., Mahin, S.A., (2000) "Property Modification Factors For Elastomeric Seismic Isolation Bearings," 12th World Conference on Earthquake Engineering, Auckand, New Zealand, January.